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INVESTIGATION OF SURFACE-STABILIZED HIGH-PRESSURE GAS DISCHARGE--ETC(U)
JUN 79 C P CHRISTENSEN N00173-78-C-0440

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A technique for stabilization of high pressure gas discharges suitable for excitation of small gas volumes at high input power levels has been identified. Application to rare gas halide lasers has been investigated.

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RESEARCH PROGRAM PLAN

The research program described herein is an experimental investigation of problems associated with the production of stable, long-duration discharges in rare gas halogen mixtures. The work is oriented toward homogeneous, high-level excitation of small gas volumes ($\sim 1\ cm^3$) with the ultimate goal being construction of a discharge-pumped rare gas halide laser which is capable of an output pulse duration greater than one microsecond.

about 1 cu cm

MAJOR ACCOMPLISHMENTS

We have successfully identified a discharge technique which allows stable, self-sustained discharge excitation of rare gas-halogen mixtures for periods of many microseconds. Prototype laser configuration based on this technique have been constructed and evaluated. Excitation levels of approximately one-half that required to reach laser threshold have been achieved in a XeF laser gas mixture. No fundamental limitations which would hinder development of an excimer laser utilizing this type of discharge have been observed.

PROBLEMS ENCOUNTERED

At the close of the contract period the major obstacle to obtaining laser operation was lack of an appropriate high-power rf source.

STATUS OF FUNDS

Amount provided:	30,000
Expenditures:	
Salaries (including overhead and fringe benefits)	23,851
Materials and Supplies	949
Travel	954
Per diem	3,975
	29,729

TECHNICAL SUMMARY

The first quarter of the contract period was devoted to an investigation of viable techniques for long-term (~1 microsecond) stabilization of a high-pressure (~1 atm) gas discharge. Initial studies were directed toward wall stabilization effects such as those commonly observed in capillary discharges. These efforts were abandoned when preliminary experiments demonstrated

that the width of the plasma sheath near a stabilizing wall decreases rapidly with pressure and is typically about 50 microns in rare gas halide gas mixtures at pressures near atmospheric. The excitation volume is thus severely limited and farther investigation of wall stabilization techniques did not appear to be justified.

An alternative discharge stabilization technique was suggested by earlier work involving CO_2 laser discharges (1)(2). In these studies capacitive ballasting of a transverse discharge was investigated and good discharge stability was observed. A sketch of this discharge geometry is shown in fig. 1. The discharge takes place between two dielectric sheets which act as a distributed capacitive ballast. Electric fields due to space charge build-up on the dielectric surfaces oppose the applied field and provide a negative feedback mechanism which greatly enhances the stability and homogeniety of the discharge. Reference 1 describes excitation of a CO_2 laser using this "transverse electrodeless discharge" technique at gas pressures near atmospheric and; without the need for discharge preionization.

There are, however, two limiting factors associated with a discharge of the transverse electrodeless type. The first of these is that separation between the dielectric sheets must be a few millimeters or less in order to assure that boundary effects at the dielectric surface dominate bulk instabilities in the gas during the discharge process. This restriction effectively limits

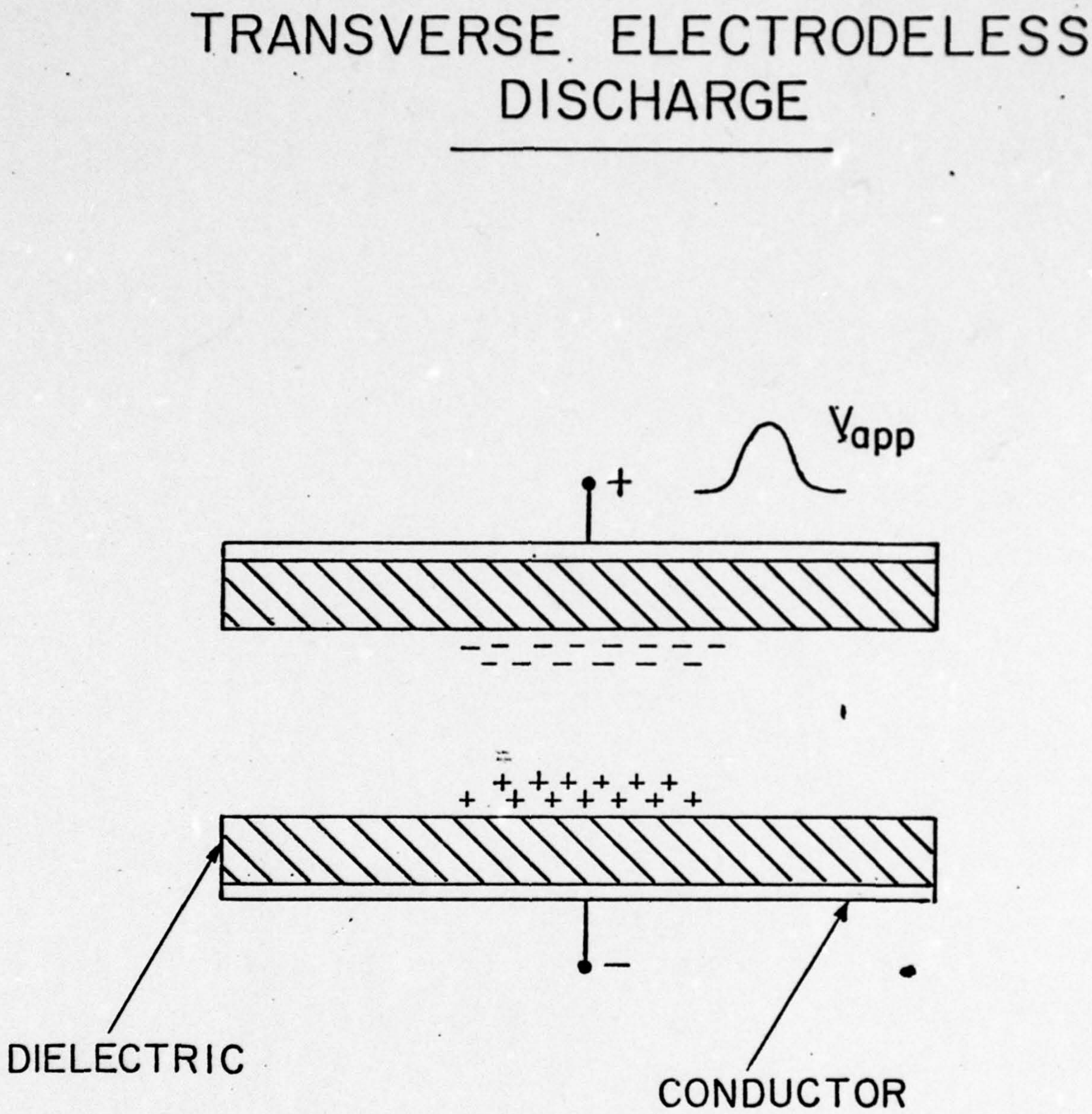


Fig. 1. Transverse electrodeless discharge geometry.

the excitation volume to perhaps a few cubic centimeters. Secondly, the energy which can be deposited into the gas with a single applied high voltage pulse or during a single half-cycle of an applied sine wave is limited by the dielectric parameters of the dielectric sheets. This energy is approximately given by the formula

$$\mathcal{E} \simeq 2\varepsilon E_d E_g \qquad (1)$$

where ε and E_d are respectively the dielectric constant and dielectric strength of the dielectric sheets, E_g is the breakdown field of the gas and $\mathcal{E}$ is the energy per unit volume deposited into the gas.

For quasi-cw excitation of rare gas halide lasers these limitations are not severe. RGH devices are characterized by high pump power requirements (~100 kw/cm^3) and operating efficiencies in excess of 1%. Practical power supply limitations would probably limit quasi-cw excitation to volumes of a few cm^3 without regard to restrictions imposed by discharge geometry. At the same time the effective quasi-cw excitation of a few cm^3 of the laser medium could result in a few kilowatts of output power. Thus the excitation volume available using this geometry is limited but adequate for most purposes.

In principle the limit on energy deposition per pulse imposed by the dielectric ballast does not restrict the attainable pump

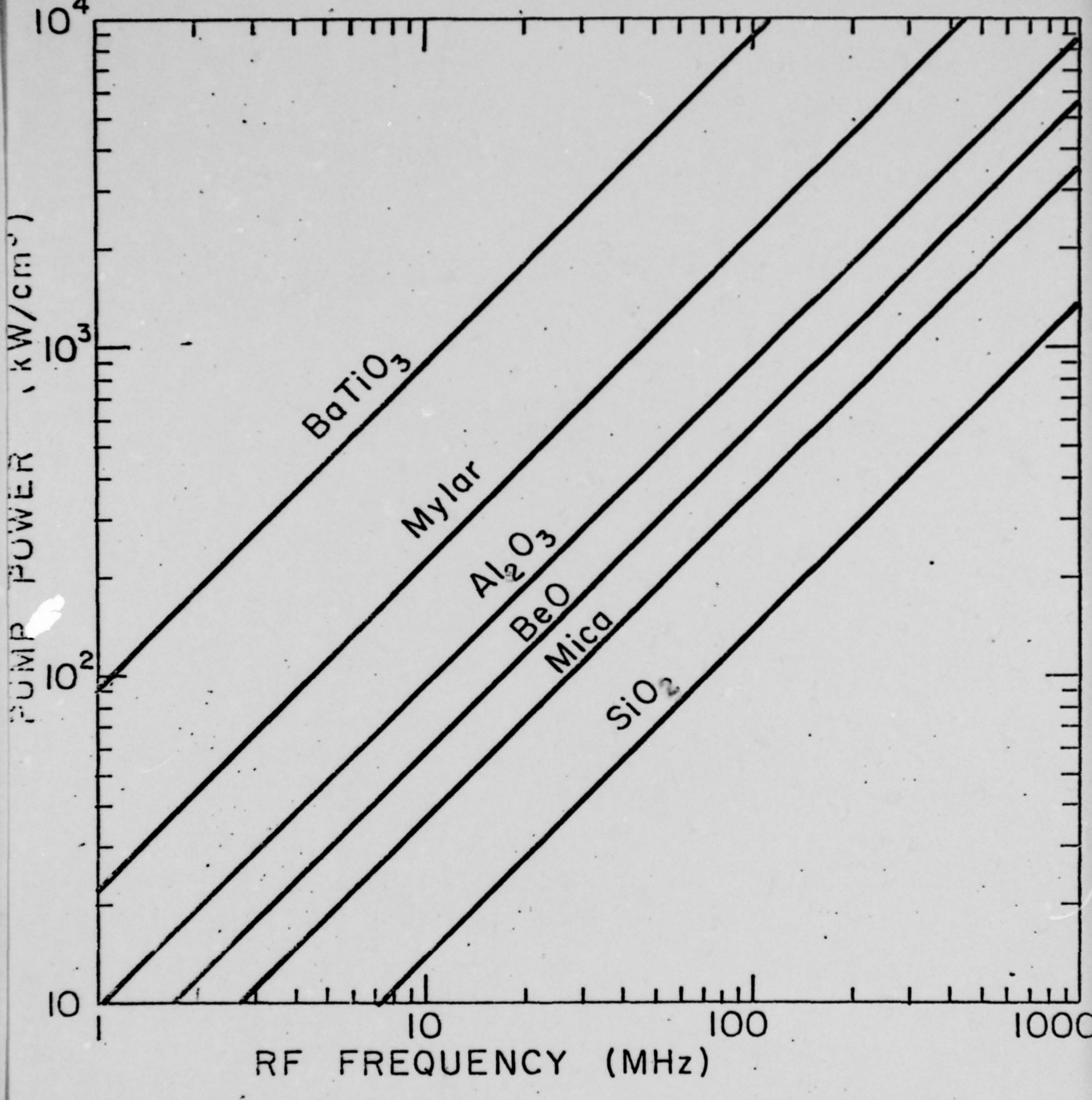


Fig. 2. Maximum pump power levels which can be attained without dielectric breakdown in the transverse electrodeless discharge geometry. A gas breakdown field of 7kV/cm is assumed.

power level provided that a high voltage rf source of adequately high frequency is used to drive the discharge. With rf excitation the pump power level, P, can be estimated using the relationship

$$P \simeq 2f\mathcal{E} \qquad (2)$$

where $\mathcal{E}$ is defined above and f is the rf frequency. Since $\mathcal{E}$ is determined by dielectric parameters, gas pressure, and mixture composition, the rf frequency required to obtain a given pump level without dielectric breakdown depends upon the ballast material. Figure 2 shows estimated pump power levels as a function of frequency for several dielectric materials and an assumed gas breakdown field of 7 kV/cm (approximately that of a one atmosphere rare gas - halide mixture). It is evident from the figure that pump levels of 100 kW/cm^3 can be achieved without dielectric breakdown at rf frequencies of tens of megahertz using materials like $BaTiO_3$, Al_2O_3, or mylar.

EXPERIMENTAL STUDIES

The above considerations suggest the possibility of long-pulse or quasi-cw operation of a rare gas halide laser using transverse rf excitation. An experimental program was launched to investigate problems associated with the actual construction of such a device. Of primary concern were the issues of discharge stability over periods of the order of 1 microsecond and difficulties which might be associated with obtaining the very high pump power levels

necessary for laser operation. Since XeF exhibits the lowest threshold pump power of the rare gas halides the investigation was concentrated on that system.

Three dielectric materials -- $BaTiO_3$, mylar, and sapphire -- were used in the experimental study. Barium titanate exhibits a high εE_d product (see equation 1 and fig. 2) and from that standpoint should be a very good ballast material. However, $BaTiO_3$ is difficult to obtain in dimensions larger than a few inches. It also possesses an extremely high dielectric constant (1200) so that sheet thicknesses of a few centimeters are required in order to obtain adequate ballasting in the 10 - 100 MHz range. Several $BaTiO_3$ sheets of thickness ranging from 1 mm to 1 cm were fabricated and experimentally tested. Construction of appropriate ballast sheets capable of withstanding high applied voltages from several smaller pieces proved to be difficult and motivated the consideration of alternative dielectrics. The epoxy and RTV bonding materials used in construction often exhibited dielectric breakdown or poor adherence, and discharge hot spots were frequently observed at adhesive-$BaTiO_3$ interfaces.

Sapphire sheets of dimensions 1x25x150mm were tried as an alternative ballast with moderately good success. The major drawback in this case was the very high applied voltage necessary to achieve the required level of excitation in the laser gas. Approximately 40 kV p-p must be applied at 50 MHz to achieve pump levels of 100 kw/cm^3 in a 1 atm XeF mixture using this ballast. Construction of the laser head to withstand such applied

voltages proved to be difficult and attempts to construct an rf source operating above 100 MHz were unsuccessful. However, discharge quality was very good, and the excellent thermal and dielectric properties of sapphire suggest that this may be an excellent ballast material in thinner sheets or when used with a higher frequency rf source.

Finally, the utility of mylar as a ballast material was investigated using a configuration like that of fig. 3(e). Although mylar is not compatible with the high temperature environment associated with quasi-cw operation of an excimer laser, it is readily available in a variety of thicknesses, is easily cut and shaped, and is suitable for microsecond-duration excitation at low repetition rates. Both 2 mil and 5 mil thicknesses have been used successfully. Dielectric lifetimes of several hours at a 1 Hz repetition rate are readily attainable although punch-through of the material occurs occasionally at high rf drive levels.

The optimum thickness of any dielectric ballast material employed in a transverse electrodeless discharge arrangement is a function of the dielectric parameters of the material and the rf drive frequency. Empirically we find that good volumetric uniformity in the discharge is obtained when the voltage across the ballast material is as large or larger than the breakdown voltage of the gas. With less ballast the discharge

develops local hot spots with consequent nonuniformity of excitation. At high ballast impedances very high voltages must be developed across the laser head to achieve the necessary excitation level. Parasitic breakdown and corona effects are difficult to avoid at high rf voltage levels and easily become a significant source of power loss. Thus the optimum ballast impedance is that which produces an rf voltage drop exceeding that across the discharge region but not so large as to produce parasitic breakdown (less than 10 kV p-p perhaps).

A variety of variations on the basic discharge geometry were investigated. These are summarized in fig. 3 which shows cross sections of some of the arrangements. Typically, an active length of 15 cm was used with all of the configurations tested and cross-sectional dimensions were of the order of a few millimeters. Geometries (a) and (b) were used in the initial experiments and allowed investigation of optimum ballast impedance. By using 1 mm and 1 cm $BaTiO_3$ sheets and a 1mm Al_2O_3 sheet ballast impedance was varied over two orders of magnitude and discharge operation evaluated. Discharge current, applied voltage, and relative UV fluorescence levels were measured for three different ballast impedances at a 30 MHz drive frequency. Fluorescence efficiency was found to improve markedly with increasing ballast impedance, and best results were obtained with 1mm Al_2O_3 ballast in configuration (a). The same configuration using 1mm $BaTiO_3$

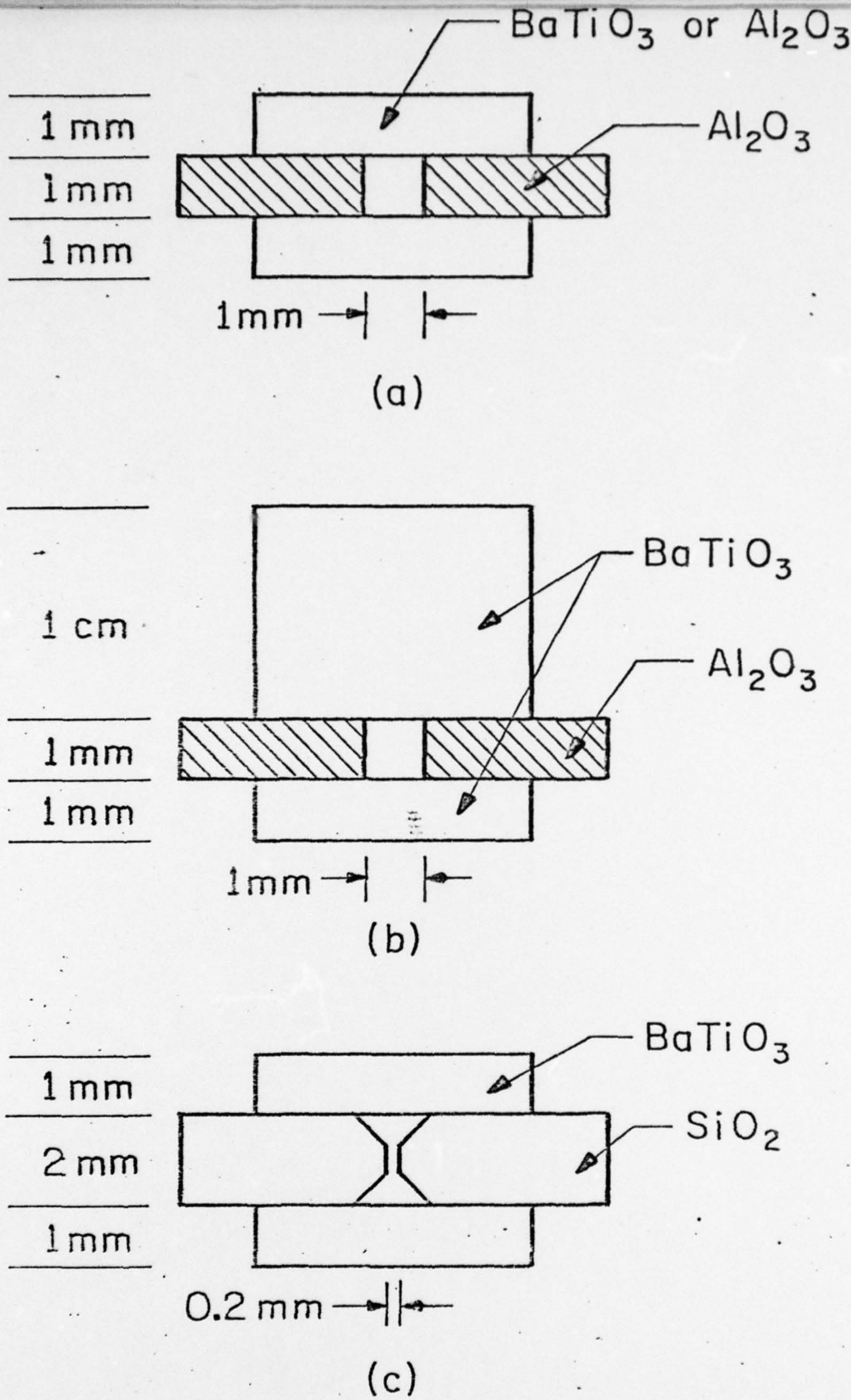
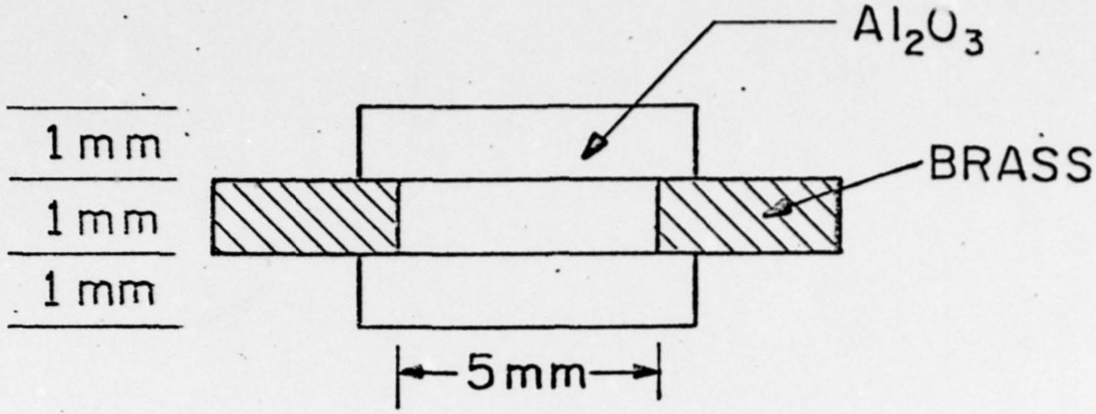
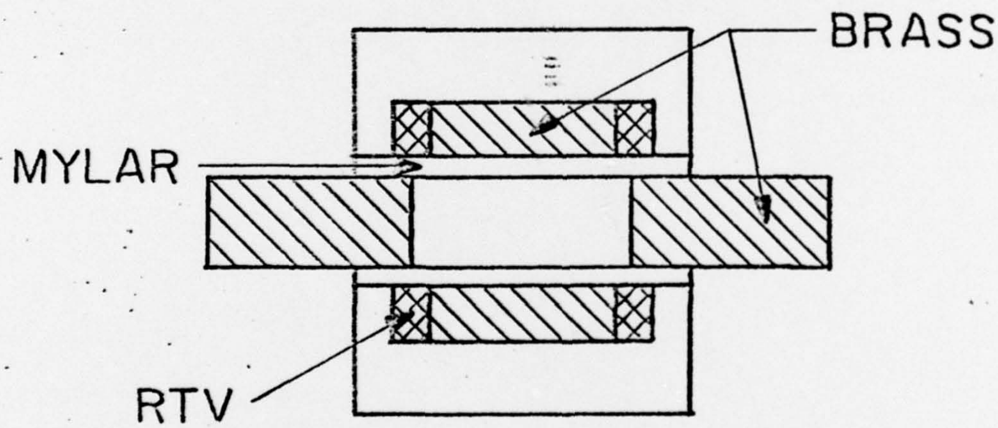


Fig. 3. Variations on the transverse electrodeless discharge geometry which were investigated experimentally. A cross-section of the laser head is shown in each sketch.



(d)



(e)

Fig. 3. (Continued)

was dramatically underballasted, and many hot spots were evident in the discharge. Configuration (c) resulted from an attempt to produce high current densities by restricting the cross-sectional area. Peak current densities of approximately 100 amp/cm^2 were obtained with this arrangement, but discharge fluorescence appeared to be lowest in the high current region, and the effort was abandoned.

Unsuccessful attempts to achieve laser oscillation in XeF using configuration (a) which will be described later led to the conclusion that the discharge was likely to be following the sidewalls rather than uniformly filling the excitation volume. To minimize this effect the wall spacing was increased from 1mm to 4mm. At the same time it was found that use of metal rather than dielectric walls did not affect the discharge quality provided that they were not connected to the rf circuit. This evolution led to configuration (d) which was found to be convenient since it allowed pulsed dc as well as rf excitation of the laser gas. Figure 3(e) shows a similar arrangement using mylar as the ballast dielectric.

<u>RF pump sources</u> constructed by Dr. F.X. Powell at NRL were used throughout the experimental phase. Preliminary studies were undertaken with a small kw, 15 MHz amplifier driven by a pulsed low-power oscillator. A clear need for higher drive power led to construction of a 50 kw, 15 MHz amplifier followed by a 100 kw, 30 MHz push-pull oscillator and finally a 400 kw, 50 MHz

oscillator-amplifier arrangement. Attempts at construction of a 100 MHz power amplifier were unsuccessful due to grid and plate resonances in the Eimac 4PR60 power grid tubes used in construction of all of the high power devices. Relatively high frequency devices proved to be desireable since they allowed a much larger degree of flexibility in choice of dielectric ballast materials and construction of the laser head. Schematic diagrams showing the electrical configuration used in the 60 MHz pull-pull oscillator and the 50 MHz high power oscillator-amplifier combination are given in figures 4 and 5. The Eimac 4PR60 power tubes proved to be only marginally suitable for these applications. They exhibit a control grid resonance at about 50 MHz and are prone to oscillate at frequencies in the 80 - 100 MHz range when driven at high input levels. In addition the screen grid lead inductance isapparently large enough to prevent effective rf grounding of the grid at frequencies above 50 MHz. However, with very careful set-up relatively large amounts of rf power can be obtained from these tubes at frequencies up to about 60 MHz.

The push-pull oscillator configuration was well suited to generation of the relatively high voltages required with heavily ballasted discharge geometries. In order to obtain higher output power, however, it was necessary to use several power tubes. An oscillator-preamplifier-power amplifier configuration was chosen for scale-up which could in principle allow parallel

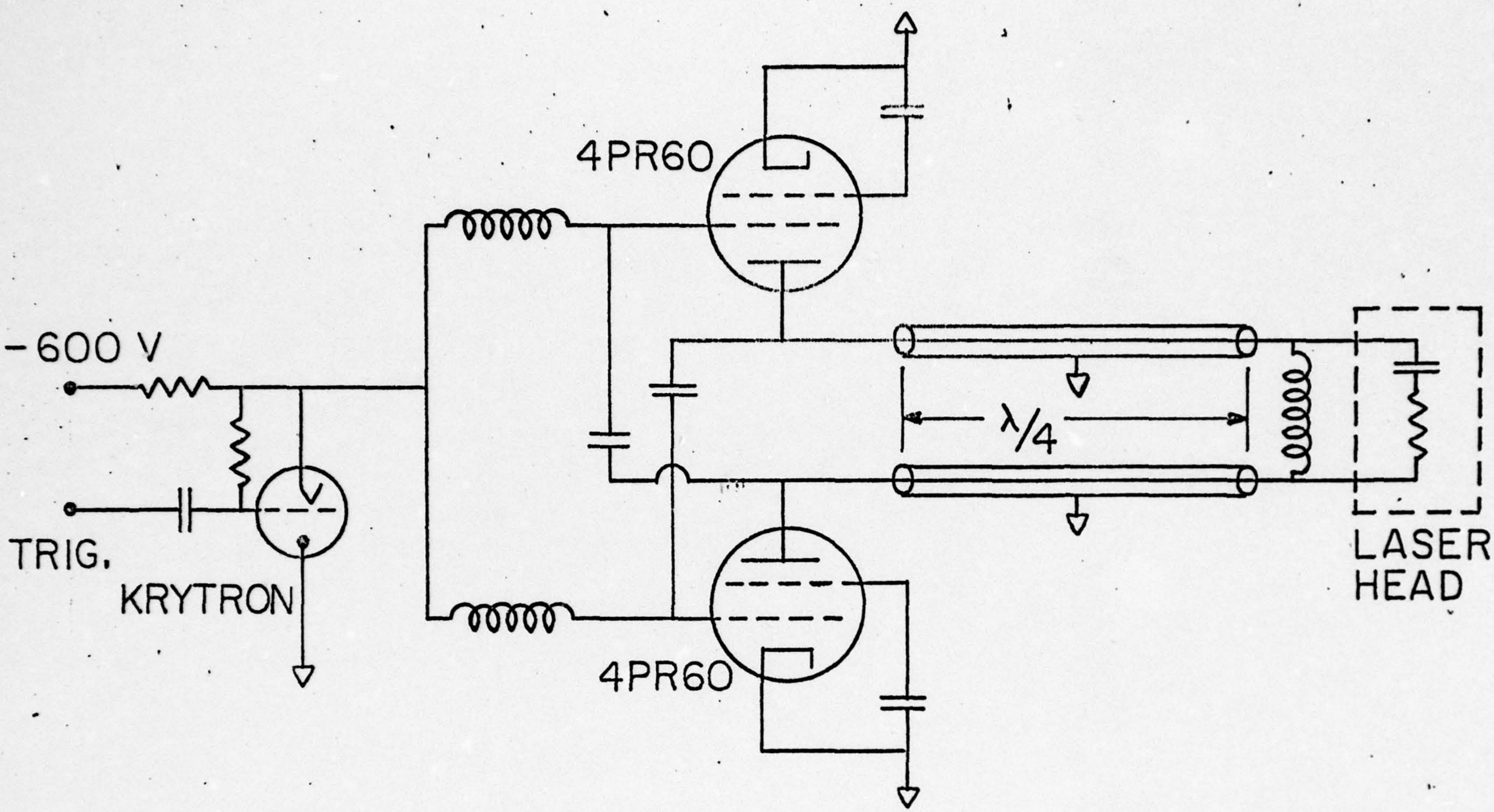


Fig. 4. 60 MHz push-pull power oscillator configuration

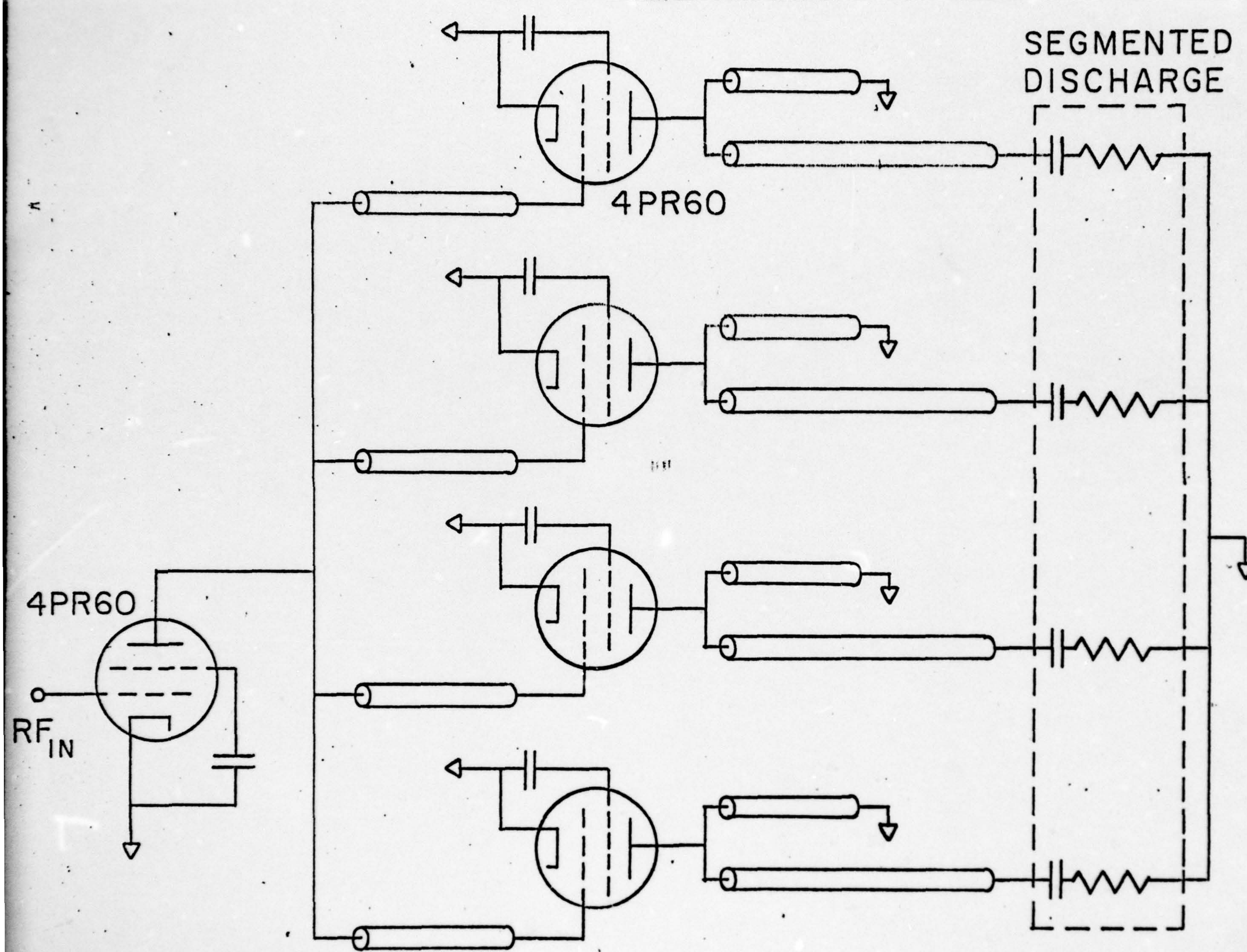


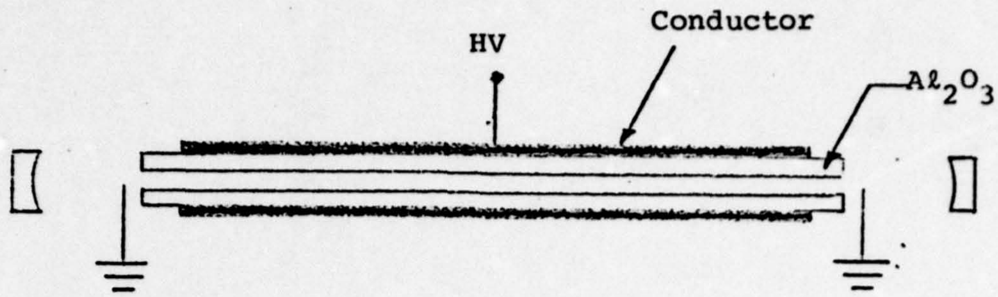
Fig. 5. 50 MHz power amplifier with preamp.

operation of a large number of tubes to obtain very high output power. It desirable to isolate the power amplifier tubes from each other as much as possible to minimize parasitic oscillations. With the electrical configuration shown in fig. 5 approximately 100 kw per tube could be delivered to a resistive matched load at a frequency of 50 MHz. To increase the inter-tube isolation the discharge was divided into four segments - one for each tube. However, the system was still plagued by parasitic oscillations, and at the end of the contract period laser pump power levels were still limited to about 40 kw/cm^3 as estimated from electrode voltages at the laser head.

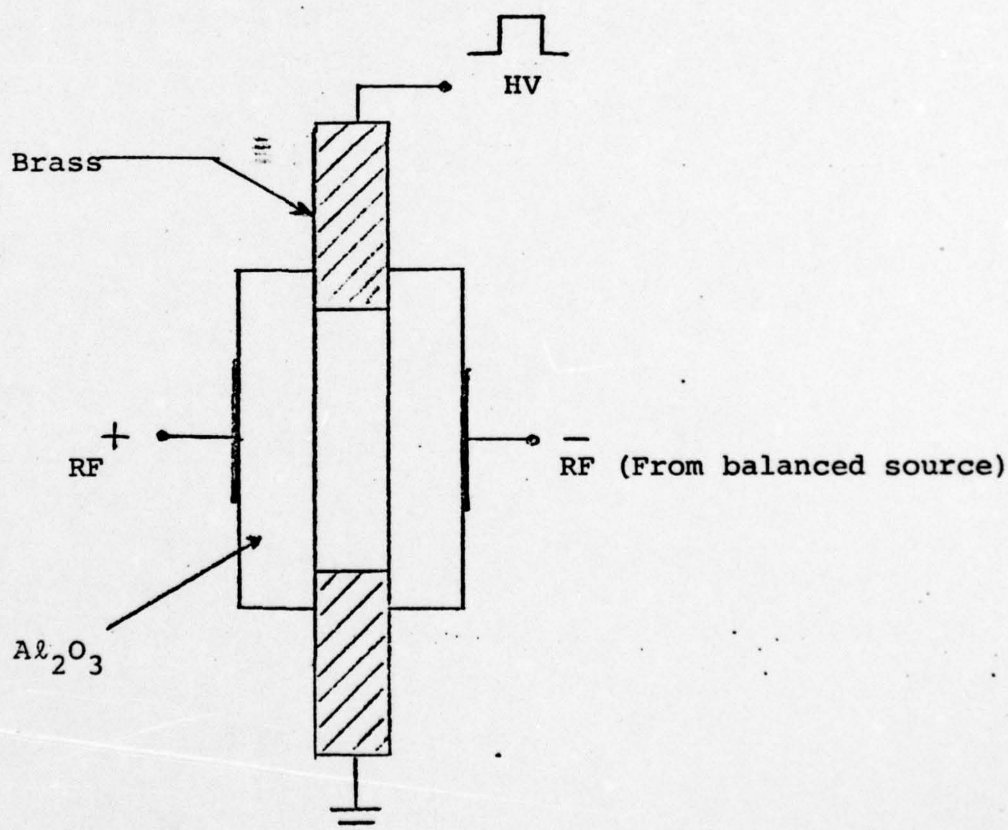
Impedance matching considerations are very important in rf discharge excitation. At pump levels of 100 kw/cm^3 the effective resistance of a 1x4x150mm discharge channel is approximately 3 ohms. On the other hand the plate impedance of the rf tubes is about 1000 ohms so that effective impedance matching is difficult but very necessary to achieve high-level excitation of the laser medium. A number of impedance transforming circuits were tried with various degrees of success. At frequencies in the 10-100 MHz range both lumped circuit and transmission line techniques can be employed. Initial experiments with 15 MHz sources used lumped circuit elements exclusively and relied primarily upon air core transformers for impedance matching. However,

for the 50 MHz sources transmission line arrangements like those shown in fig. 5 were found to be simpler and more effective. An inductive stub is placed in parallel with the rf tube and a section of RG-8 cable is used to connect the tube to the discharge. Tuning is accomplished by adjusting the two cable lengths for optimum power transfer. It was found experimentally that large fractions (>50%) of the available rf energy could be transfered to the discharge using a well-tuned transmission line matching circuit.

Laser Experiments. In order to monitor progress toward achieving excimer laser operation with rf excitation it is desirable to have a means of monitoring gain in the excited medium and knowledge of the excitation level required to reach threshold. Consequently several of the discharge configurations were designed so that the medium could be excited by conventional discharge techniques as well as by the rf field. Two of these are shown in fig. 6. The first of these is a variation on the capacitively coupled longitudinal discharge first reported by Newman [3] and the second is a conventional transverse discharge preionized by the rf field. Both of these designs were found to be suitable for estimating threshold fluorescence levels and convenient for mirror alignment. The Newman arrangement lased with either pulsed dc or rf voltages applied to the laser electrodes and may thus be considered to be the first rf driven XeF



(a) Newman configuration



(b) RF preionized discharge

Fig. 6. Discharge configurations used in laser experiments

laser. However, optical pulse durations were only ~15 ns with both types of excitation. Comparison of discharge fluorescence with laser output using rf excitation showed that laser operation ceased before the 350 nm fluorescence reached a maximum. This was interpreted as evidence of collapse of the discharge to the walls shortly after breakdown. This kind of phenomena was not unexpected since the capacitive ballast would not be effective for stabilization of a longitudinal current flow.

Fluorescence levels at threshold were observed by using a biplanar photodiode to monitor excimer emission and operating the laser near threshold with one of the conventional discharge schemes. By comparing these fluorescence measurements with those obtained with transverse rf excitation the rf drive levels required at threshold can be estimated. The fluorescence levels obtained with the highest rf drive level achieved (40 kw/cm^3) in a $He/Xe/NF_3$ mixture were approximately one-half of the expected threshold value. Laser oscillation was not observed at this drive level even in a high Q cavity formed by dielectric mirrors of 99% reflectivity.

Although laser threshold was not achieved in these experiments, observations of discharge fluorescence suggest that long term discharge stabilization was obtained. The discharge visually appeared to be a uniform glow with no evidence of arcs

or streamers at pressures extending to 1000 torr. Photodiode measurements (see fig. 7) showed the UV fluorescence to exhibit a short peak at breakdown followed by a long, slow decay which extended over several microseconds and may arise from NF_3 consumption or gas heating. There is again no evidence of arc formation. These results suggest that we have successfully stabilized the discharge so that uniform, long-term excitation of a high-pressure rare gas halide mixture is now possible. Extension of this approach to slightly higher excitation levels seems straightforward.

Summary. We have investigated techniques for stabilization of rare gas halide discharges, and a method of discharge stabilization at high pressures, high excitation levels, and for almost arbitrarily long periods has been identified. The transverse electrodeless discharge using rf drive is suitable for excitation of gas volumes of a few cubic centimeters and does not require preionization. It has the added advantage of allowing the discharge medium to be contained in a clean, inert, metal-free vessel - for example one constructed totally of alumina.

The application of this discharge to excitation of a XeF laser has been investigated and pump power levels of approximately one-half the threshold level have been attained. The primary limitation to date has been the rf source. The preliminary experi-

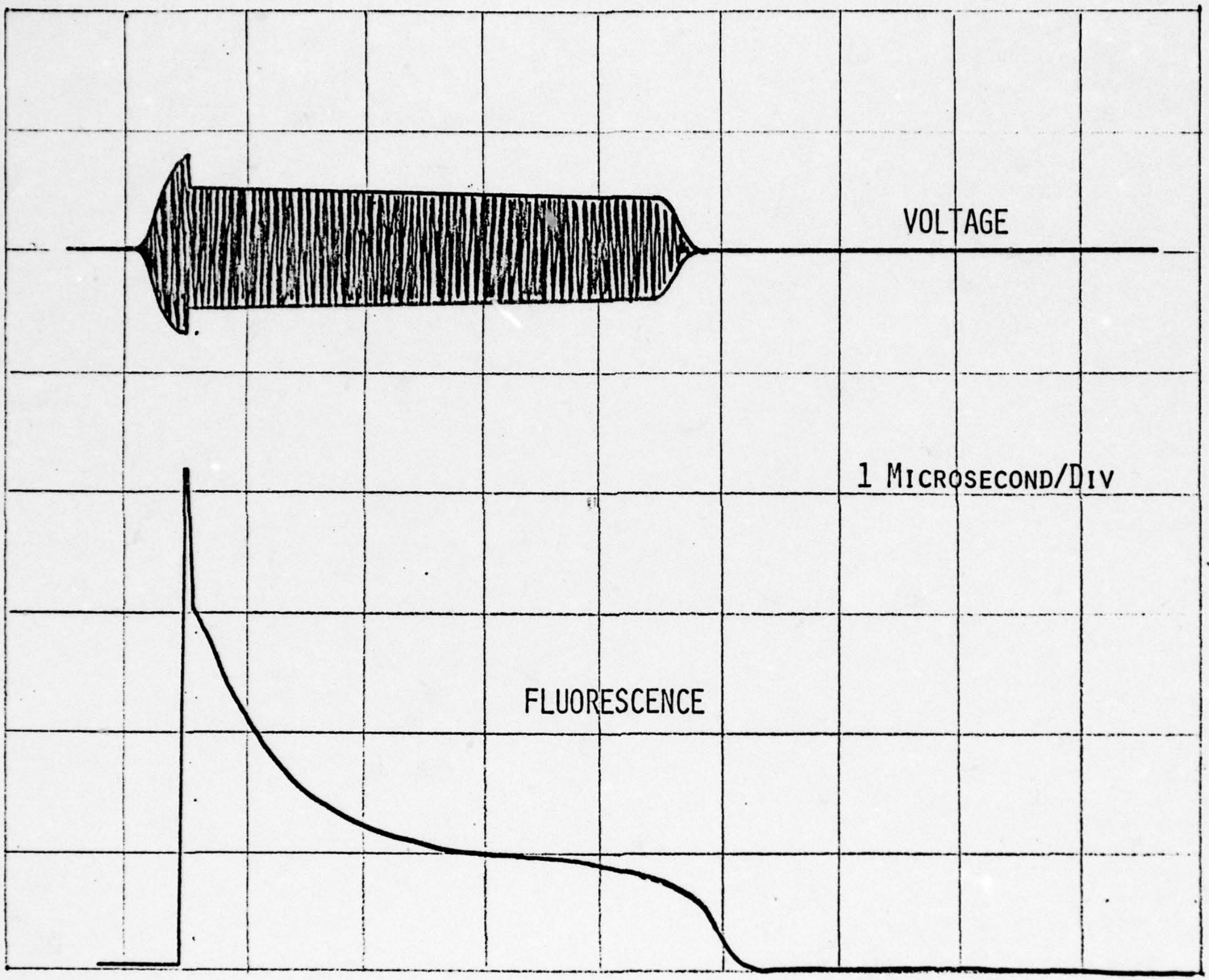


Fig. 6. Applied rf voltage and XeF fluorescence obtained from a 1 atm $He/Xe/NF_3$ mixture.

ments described here have uncovered no fundamental limitations which would hinder development of a long-pulse rare gas halide laser using rf discharge techniques. Rf source requirements are substantially below the capabilities of currently available rf technology. It appears that with more effective utilization of available technology long-pulse laser operation can be achieved.

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